FINAL REPORT
Nonr(G)-00045-62
NR 046-792

"RESEARCH IN STELLAR SPECTROSCOPY"

A. B. Meinel

E. F. Carpenter
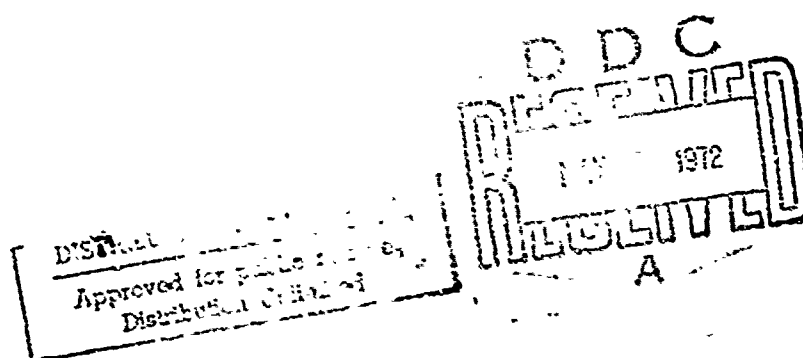
FINAL REPORT
Nonr(G)-00045-62
NR 046-792

"Research in Stellar Spectroscopy"

This research covered by this grant to Dr. Edwin F. Carpenter, was delayed in completion due to the death of Dr. Carpenter. The project has been completed by Dr. A. B. Meinel.

The project involved the modification of the Carpenter nebular spectrograph to permit a wide range of applications, and its use in research on galaxies and faint stars. It also involved partial support for the construction of a stellar spectrograph for the Cassegrain focus of the 36-inch Steward telescope. All phases of this project have been completed.

One of the major tasks was the rebuilding of the instrument to use glass plates instead of film. Film emulsions are generally slower than those available on glass plates; moreover, the minimum order for film is quite expensive. In order to modify the camera for plate use, it was necessary to install a field flattening lens and move the Schmidt plate 1/2 inch closer to the camera mirror.

Fig. 1 shows the modified plate holder system. The field lens is fixed to the focus slide and not to the plate holder itself.

Re-allignment of the spectrograph is a tedious job. The test setup is shown in Figs. 3a and 3b. A test lens forms a star image on the slit of the spectrograph. The camera then focuses this image on the photographic plate (the grating is removed during this test). A 40X microscope is used to examine the image viewed on the raw emulsion.

The instrumentation has proven to have a higher optical resolution than anticipated. The spectrum of molecular hydrogen using the rebuilt nebular spectrograph is shown in Fig. 4.

The instruments have been used for two Ph.D. dissertations to date; one by A. Aveni on the spectra of T-Tauri stars and a second by E. Moore on the stellar content of galaxies. They have also been heavily used by the staff for studies of emission regions (Dr. Lynds), and MK standard stars (Meinel). The material will appear in publication form in the near future. A publication text by A. Aveni is attached. A typical plate format for stellar observations is shown in Fig. 6.

The nebular spectrograph has played an important role in opening up a new field of research. Since it is relatively portable, the instrument was loaned to Dr. Bashkin for the initial experiments with the spectra emitted by fast ions from nuclear accelerators. This work has been highly successful and numerous publications have resulted from the discovery made using this spectrograph. Fig. 2 shows a spectrum of nitrogen taken with this spectrograph. A microdensitometer tracing of this spectrum with identifications is shown in Fig. 5.

The work planned by Dr. Carpenter, on the spectra of faint interconnections between galaxies, had only been started at his death. No further work has been done in this area due to pressures of other requirements. We hope, however, that this area of study will be followed in dissertation research in the near future.

In conclusion, we would like to express our appreciation for the very substantial assistance that the office of Naval Research has given us. We expect to see this assistance materialize in the form of many dissertations and publications in the following years.
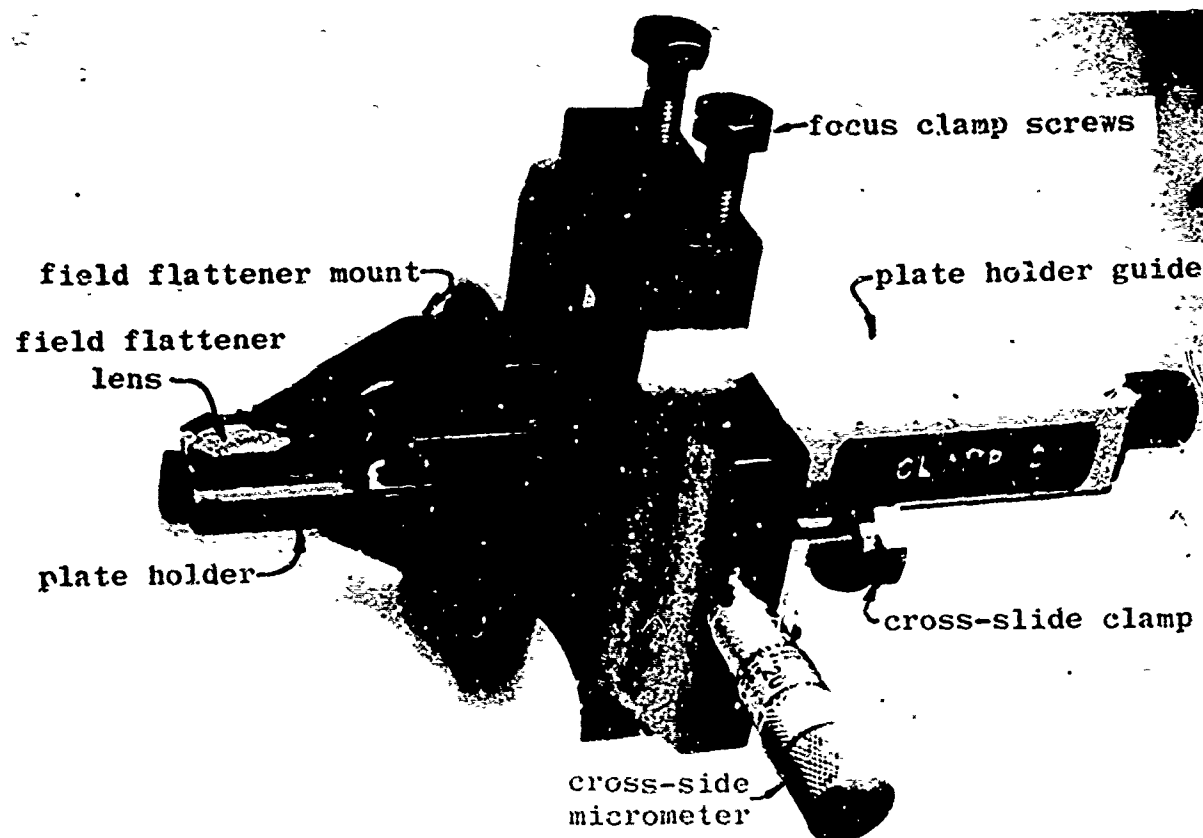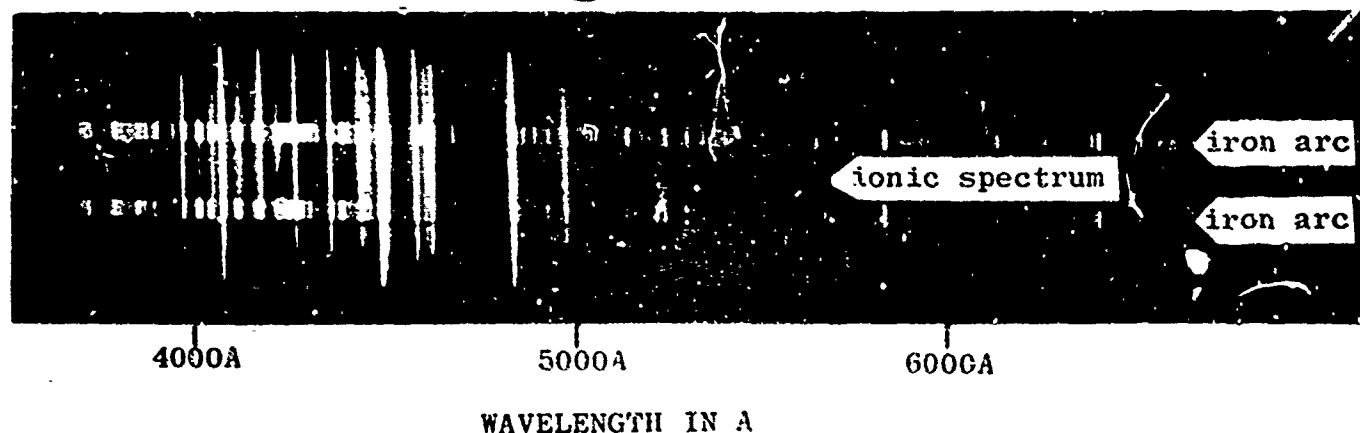
-3-

focus clamp screws

plate holder guide

field flattener mount

field flattener lens

plate holder

cross-slide clamp

cross-side micrometer

PLATE HOLDER DETAIL FOR MODIFIED NEBULAR SPECTROGRAPH

Fig. 1

ionic spectrum

iron arc

iron arc

4000A   5000A   6000A

WAVELENGTH IN A

SPECTRUM OF 2 MEV NITROGEN ATOMS EXCITED BY CARBON STRIPPING FOIL

This spectrum was taken by Meinel and Bashkin during a pioneering experiment at the High Voltage Corporation laboratory, Burlington Mass, November 22, 1963. Exposure 30 minutes, beam current 10µA,
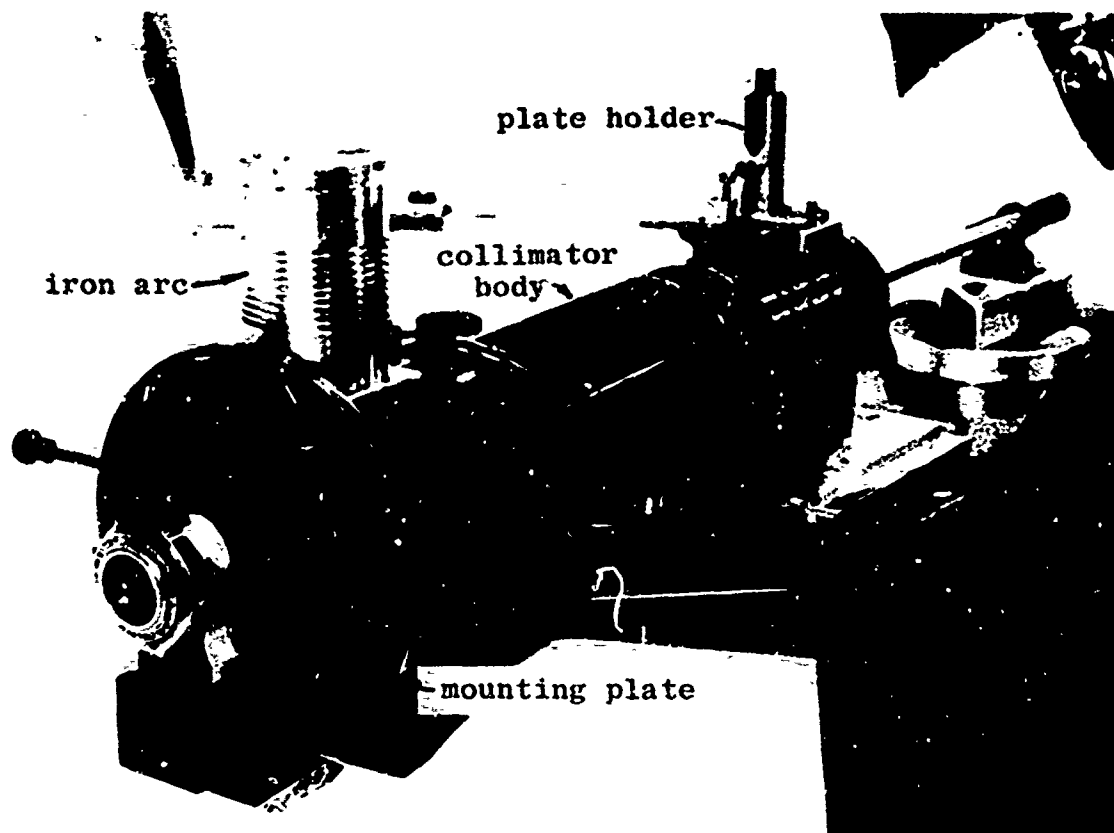
Fig. 2
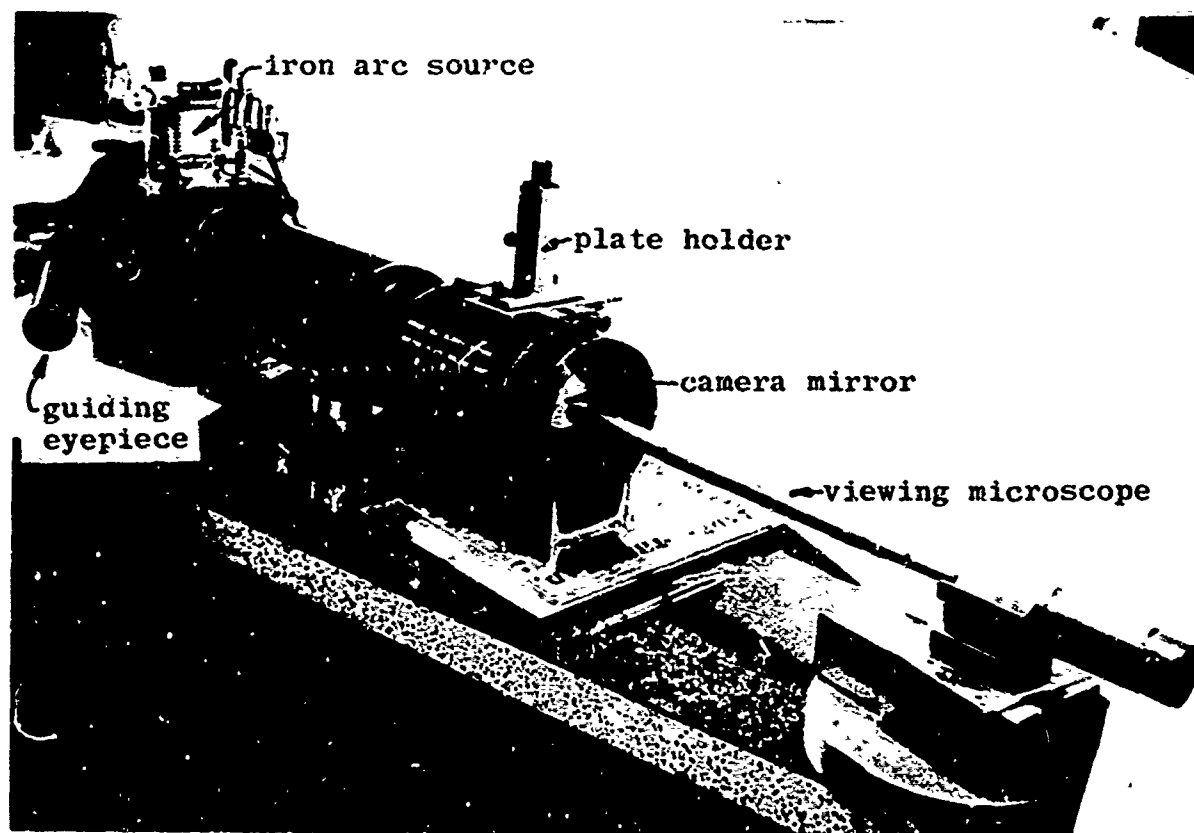
plate holder

iron arc

collimator body

mounting plate

Fig. 3a

iron arc source

plate holder

camera mirror

guiding eyepiece

viewing microscope

TEST SETUP FOR RE-ASSEMBLY OF THE MODIFIED NEBULAR SPECTROGRAPH

Fig. 3b
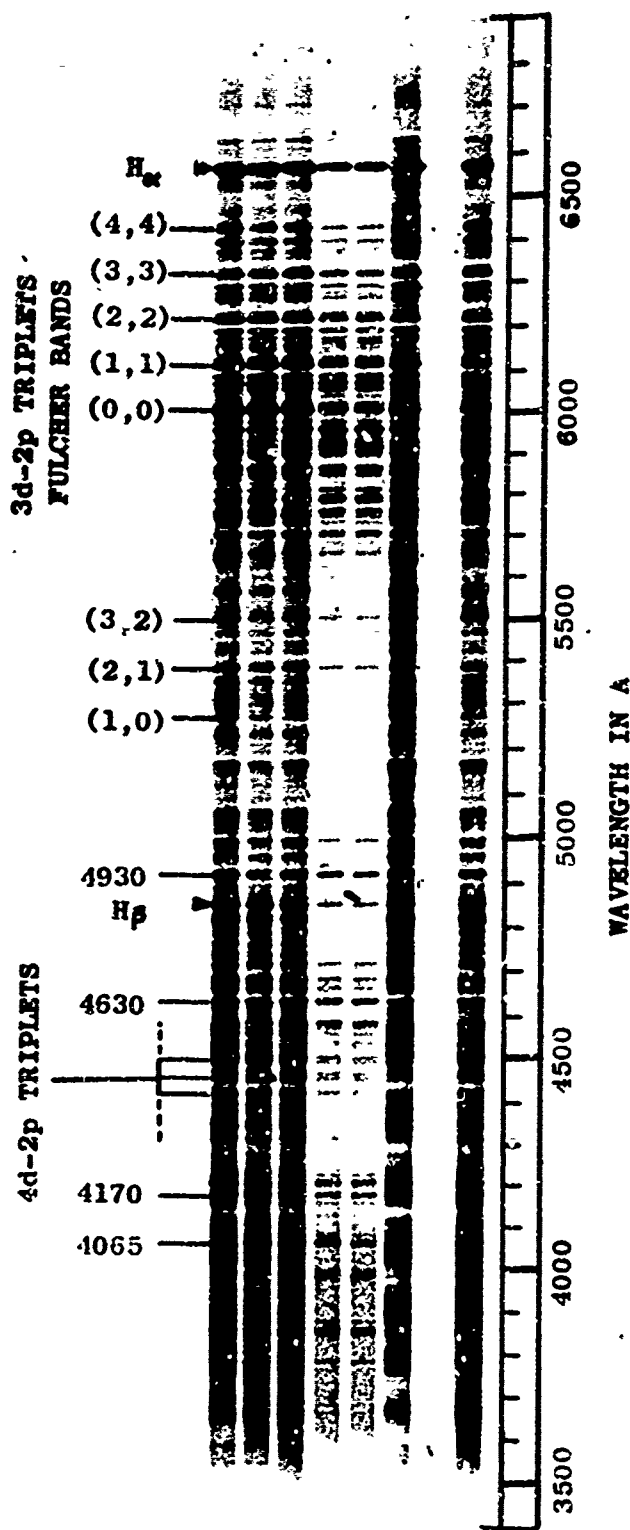
THE SPECTRUM OF MOLECULAR HYDROGEN TAKEN WITH THE MODIFIED
F/0.8 ZERO-DEVIATION NEBULAR SPECTROGRAPH

The different spectra show the effect of admixed air on the
spectrum

Fig. 4
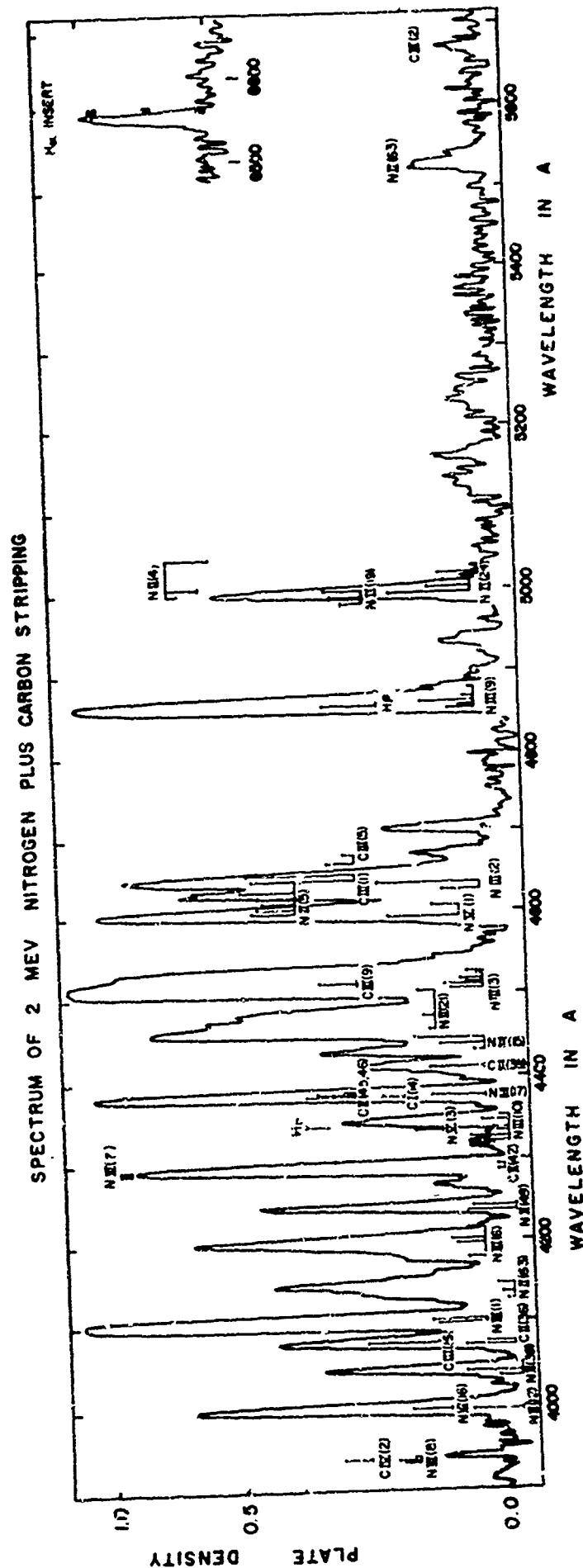
MICRODENSITOMETER TRACING OF 2 MEV NITROGEN SPECTRUM

The identifications in this spectrum show a carbon impurity
due to CO+ in the ionic beam. Subsequent tests with isolated
atomic spectra show spectra of high purity.

Fig. 5

GOV
HD 13974

T-Tau

AOV
4 Aur

RW Aur

iron arc

iron arc

TYPICAL PLATE FORMAT USED WITH THE MODIFIED NEBULAR SPECTROGRAPH

This plate, from the PhD dissertation by Anthony Aveni, contains the calibration standard stars HD 13974 and 4 Aur, top and lower middle spectra, plus the two program emission-type objects that are prototypes for the "T-Tauri" and "RW Aurigae" emission stars. The two bands on either side of the emission stars are comparison spectra from an iron arc, used for wavelength measurement uses.

Fig. 6

The Effect of Line Emission Upon the B-V Colors of T Tauri Objects*

Anthony F. Aveni

Steward Observatory, University of Arizona, Tucson, Arizona

Abstract

A method has been developed to determine the influence of line omission upon the UBV colors of the T Tauri objects T Tau and RW Aur. Calibrated spectra of th se objects were obtained using the Steward Observatory 36-inch telescope and the Carpenter F 0.8 nebular spectrograph, recently rebuilt for use with glass plates with the assistance of ONR grant number Nonr(G)-00045-62. These spectra were corrected for instrumental and atmospheric effects and two colors were computed from microdensitometer traces of each spectrum: 1) the continuum color devoid of emission lines, and 2) the color including emission lines. The latter color can then be directly compared to the observed photometric color. Comparison of the observed B-V colors with the computed B-V shows good agreement, indicating that the photographic corrections were properly assessed. The difference of the colors obtained for the continuum, $(B-V)_c$, and the continuum plus line emission, $(B-V)_{cl}$, shows apparent variations between $0^m.07$ and $0^m 14$ and T Tau and between $0^m 6$ and $0^m 15$ for RW Aur, with some dependence upon continuum color. The line emission parameter shifts the position of both stars to the right in the $\log L/L_o$, $\log Te$ diagram; this can be interpreted as a correction to the contraction age of up to 20%.

This method of computing colors for emission is demonstrated to be more accurate than that of Smak (1964) who uses photometry only. The method employed in the present study is, however, quite laborious due to the problems introduced by the non-linearities of the photographic process.

Since unresolved line emission is almost certain to be present in the spectra, the emission line correction is to be regarded only as a lower

limit. The B region, for example, covers a portion of the spectrum where many metal lines occur, so a contribution of these lines would make the corrected B-V color determined in this study still too blue.

The previous spectral type assigned to both stars is G5Ve, though estimates have ranged from G0 to K2. From the intensity distribution of the continuum the types F7-K0 are assigned to T Tau, F0-G8 to RW Aur. This variation appears to be larger than the error of measurement and probably indicates a real variation of the stellar continuum.

I. Introduction

The principal aim of this research has been to interpret the effect of line emission upon the B-V colors of T Tauri objects. The program is intended to determine (a) the "emission-tracks", as contrasted to the reddening or blanketing tracks in the case of absorption effects, in the UBV diagram and (b) the energy distribution in the continuum after correction for the presence of emission. The spectral types of the T Tauri class are generally regarded to be of types G0-K5. One should therefore find that the corrected continua agree with the absolute energy distribution curves for main-sequence stars as published by Code (1960).

The question of the effect of line emission upon UBV colors has been investigated in the past by Varsavsky (1960) and more recently by Smak (1964). Varsavsky compared his measurements of the B-V color of several T Tauri variables with Joy's (1949) spectral types for these stars. He found that for a given effective temperature as determined from spectral type, the B-V color is up to $0.^m8$ bluer than that for main sequence stars of the same spectral type. Varsavsky proposed that at least part of the discrepancy between the T_{eff} vs B-V relationship for late type main sequence stars and T Tau variables is due to the influence of emission lines upon the continuous spectra of the latter. It should be pointed out that the spectra of these stars are very difficult to classify owing to the multitude of emission lines which overlie the diffuse absorption features. Furthermore, there is no evidence to support the hypothesis that the spectral types of these variables remain constant in time. Kuhi (private communication) has noted marked changes in the spectra of several T Tauri stars. Varsavsky found that the largest discrepancies generally occurred for those stars having the strongest emission line spectrum. The strongest emission lines observed in T Tauri spectra are those of the Balmer series and CaII, H and K. Of these, the B filter is highly transparent

to H γ and Hδ and less transparent to the remaining lines. Observations
with the V filter, however, are affected only slightly by the presence of
Hα and Hβ (The V filter transparency is 10% at Hβ and 5% at Hα) and not
at all by the remaining lines.

Smak (1964) has devised his own photometric system containing an
"emission free" color index, β-V; the β filter combination is transparent
between Hγ and Hβ while V is the V magnitude of the UBV system. He has
evaluated the emission line effect by comparing the color indices B-V and
β-V for twenty-six T Tauri type stars in the Taurus dark cloud. T Tauri
stars are found to deviate from the standard B-V vs β-V relationship for
normal main sequence stars by up to $0^{m}5$. Smak's method provides an immedi-
ate answer to the question whether an emission line influence exists. An
exact evaluation of the effect, however, is not possible, since many FeI
and FeII lines exist in the range in which the β filter is transparent.
This is especially true in the spectra of such advanced T Tauri stars as
RW Aur. Ideally, one wishes to determine the difference between the B-V
color of the continuum devoid of all emission lines, and the observed B-V
color.

In preparation for this work, the author obtained an extensive series
of plates from the Mount Wilson Observatory through the assistance of
Dr. A. H. Joy. These included some of the objects for which he has pub-
lished spectra (Joy (1945)). A preliminary study of these plates indicated
that significant corrections to the measured colors for the presence of
emission are found for nearly all objects. It must be admitted that the
study of these older spectrograms in which the calibration is to some
extent open to uncertainties must be accorded low weight even though the
effect seems to be too large to explain in this manner. One possibility to
explain the discrepancy is the presence of many faint and unresolved
emission lines, especially in the region λ 4200-4400Å.

II. Method of Investigation

Low dispersion spectra (240Å/mm) of two bright T Tauri stars, T Tau and RW Aur, were obtained with the 36-inch telescope of the Steward Observatory. From microdensitometer tracings of these spectra two B-V were computed:

1) The color $(B-V)_c$ of the continuum devoid of emission lines.

2) The color $(B-V)_{cl}$ of the continuum with the emission lines included. The latter color was compared with the photometric B-V color observed at the time the spectra were taken.

The reduction program is a laborious one principally because of problems encountered in the photographic reductions.

A brief outline of the method employed to obtain true UBV magnitudes follows:

1. The basic format adopted involves the observations of (1) the program star, for example T Tau; (2) an AOV standard star, for example ⲪLyr, which can be assumed as representative of the Code (1960) standard energy distribution for an AOV star; (3) a star of nearly the same spectral type as the program star, for example HD157214 (GOV). (4) a wavelength comparison, Fe for the wide spectral sensitivity of the 103a-F plate (3500-6800Å with the Steward instruments); (5) a multi-step tungsten lamp comparison spectrum is normally placed on the plate at opposite sides of the above spectra. In this program, however, this problem is circumvented by taking the spectrum of a Code standard, whose intensity distribution is already known, through the step wedge.

2. Simultaneous BV measures and spectra of the program T Tauri objects were required, the former with the Kitt Peak 16-inch telescope and the 21-inch telescope at the Catalina Station (Lunar and Planetary Laboratory), the latter with the 36-inch telescope

at the Kitt Peak Observing Station of the Steward Observatory.

3. The wavelength distribution of the flux emitted by the Code standard star at several intensity increments is used to obtain the characteristic curve and the wavelength sensitivity for the plate.

4. This information yields a set of corrections to be applied to the observed stellar spectra to obtain absolute intensities for both the continuum and emission features.

5. Those portions of the area under the stellar curve which fall within the BV passbands are numerically integrated using the known transmission functions for these passbands. Thus, one obtains "synthetic" BV magnitudes for the stellar body after determination of the transformation equation through use of the AOV star.

6. The measured BV magnitudes are then compared with those computed to determine the effect of emission lines in altering the positions of the objects in the color magnitude and two-color diagrams.

7. One can obtain an independent evaluation of the effect on the BV magnitudes from the emission lines by reducing the observed line intensities in the manner of step 5. If proper evaluation of each step in the reduction has occurred, the line plus continuum color and the observed photometric color will agree. This procedure, therefore, provides a valuable crosscheck. The plate format is illustrated in Fig. 1.

The present method has the distinct advantage that it treats each emission feature separately. The flux emitted by every resolvable feature is numerically integrated into the B-V color. There is no question that the multitude of photographic corrections have been properly assessed. The method is accurate enough to predict the B-V colors of standard stars to within $\pm$ .016 p.e.

TYPICAL PLATE FORMAT USED WITH THE MODIFIED NEBULAR SPECTROGRAPH

Fig. 1 Observing Format

Table 1 demonstrates the ability of the program to predict the B-V colors of standard stars. The third column, following the name of the standard and Steward Observatory plate number is the catalog value of the B-V color; the fourth column lists the color computed from the reduced microdensitometer tracing of the spectrum. The last column gives the difference of the two. Simultaneous photometric colors of the T Tauri variables should agree with those computed from the spectra. This provides a second test of the validity of the spectroscopic method. Complications enter, however, because of the extremely rapid variations in light cycle and continuum color coupled with the long exposure times required to obtain a spectrum. During a single two hour exposure the B-V color determined photometrically was found to vary by up to $0^{m}.10$. The photographic process places severe limits on the technique. Since the number of low excitation Fe, Ti, and Cr lines common to these spectra increase toward the ultraviolet, the U-B color also needs to be corrected. The emission tracks in the two color diagram are not really lines of constant U-B but probably slope downward and to the right. The correction to the U magnitude simply cannot be done photographically.

III. Results

The principal result of this work is that the computed emission line flux marks the true B-V color of T Tauri objects by up to $0^{m}.15$. The parameter δ, defined as the difference between the line free color, $(B-V)_{c}$, and the color with line emission contributions included, $(B-V)_{cl}$, varies between $0^{m}.06$ and $0^{m}.15$ (mean = $0^{m}.11$) for RW Aur and between $0^{m}.07$ and $0^{m}.14$ (mean = $0^{m}.10$) for T Tau. Table 2 summarizes the results. The fourth and fifth columns list the continuum and continuum + line colors respectively. Note the wild variations of the emission line parameter, δ, shown in column 6. If one were to include the unresolved emission lines in the B region the blueing effect caused by the presence of line emission would be even more vivid. The last

Table 1 Computed and Observed Colors of Standard Stars

Object	Plate No.	Observed B-V	Computed $(B-V)_c$	$(B-V)-(B-V)_c$
✗ Cet	23	÷0.68	÷0.67	÷0.01
ξ Eri	25	÷0.89	÷0.88	÷0.01
μ Her A	26	÷0.75	÷0.74	÷0.01
η Cep	26	÷0.92	÷0.95	-0.03
13974	28	÷0.61	÷0.65	-0.04
ρ Com	199	÷0.57	÷0.59	-0.02
61ygA	205	÷1.19	÷1.20	-0.01
61CygA	207	÷1.19	÷1.21	-0.02
16CygA	209	÷0.64	÷0.61	÷0.03
16CygA	210	÷0.64	÷0.61	÷0.03
ε Gem	237	÷0.32	÷0.29	÷0.03
ε Gem	240	÷0.32	÷0.31	÷0.01
ε Gem	242	÷0.32	÷0.29	÷0.03

Table 2 Summary of the Effect of Line Emission Upon B-V Color

| Object	S.O. Plate No.	Date	$(B-V)_c$	$(B-V)_{cl}$	δ	Remarks Concerning Concurrent Photometry
RW Aur	23	1963 Oct. 13	÷0.67	÷0.57	0.10	
	25	1963 Oct. 14	0.51	0.36	0.15	
	26	1963 Oct. 15	0.60	0.47	0.13	
	28	1963 Oct. 17	0.70	0.55	0.15	$0.50 < B-V < 0.60$; $8.53 < V < 8.56$
	232	1965 Jan. 1	0.43	0.37	0.06	
	236	1965 Jan. 27	0.30	0.22	0.08	
	240	1965 Jan. 29	0.43	0.36	0.07	
T Tau	25	1963 Oct. 14	1.11	0.99	0.12	$1.00 < B-V < 1.05$; $9.90 < V < 10.02$
	28	1963 Oct. 17	1.28	1.14	0.14	$1.14 < B-V < 1.17$; $9.53 < V < 9.57$
	232	1965 Jan. 1	1.19	1.08	0.11	
	236	1965 Jan. 27	1.07	0.98	0.09	
	237	1965 Jan. 28	1.20	1.11	0.09	$B-V = 1.17^*$ $V = 10.39^*$
	240	1965 Jan. 29	0.94	0.87	0.07	
	242	1965 Feb. 19	1.16	1.07	0.09	

* One Observation only.

column gives the results of the photoelectric photometry done concurrently with the spectra. While this is seen not to provide a strigent test of the method the colors observed with the photometer do not conflict with the computed colors including line emission. The photometric colors more nearly approximate $(B-V)_{c1}$ than $(B-V)_c$ as theory predicts.

The problem of emission line identification is complicated by a number of effects:

1) Extreme crowding of lines occurs in all active T Tauri spectra.

2) The ultraviolet and blue regions of the spectra contain strong emission continua.

3) It has been necessary to use low dispersion equipment in order to limit exposure times on the 36-inch instrument to about three hours.

In spite of these complications 56 emission features are observed over the region of 103a-F plate transparency. Two thirds of these features lie between CaII H and K and Hβ and arise from low levels of excitation in the metals. Neutral and singly ionized iron contribute a majority. Redder continuum color seems to be associated with larger values of δ . This is shown in Fig. 2 where δ is plotted as a function of $(B-V)_c$. The explanation may be connected with the fact that most of the emission lines in T Tauri spectra are located in the blue region. When the blue continuum becomes depressed relative to the red some of the lines which were lost in the intense continuum on previous spectrograms show up against the less dense background. An alternative explanation would require one to devise a special physical process in the atmosphere of T Tauri stars which produces greater emission line flux at the same time the continuum flux diminishes in the blue. The explanation that the effect is extrinsic seems much simpler. "Emission tracks" drawn in the color magnitude and two color diagrams vividly illustrate the magnitude of the line emission correction. The shift toward the right in

Fig. 2. Line Emission Parameter (δ) vs. Continuum Color ($(B-V)_c$)

+ T Tau   • RW Aur.
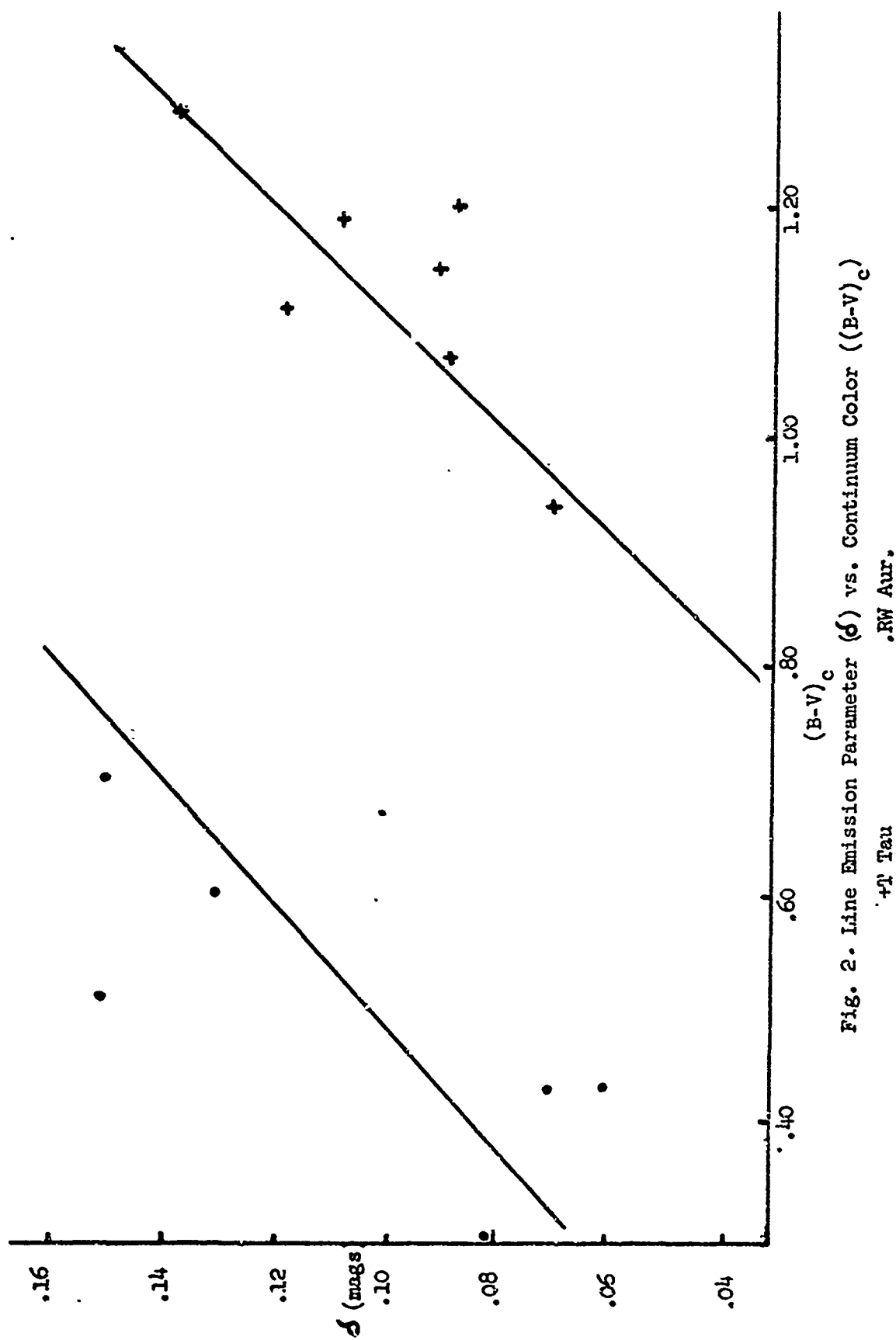
the color magnitude diagram caused by removal of the emission lines doubles the distances of these stars from the main sequence; this can be interpreted to mean that these objects are as much as 20% younger than previously believed; the corresponding change $\Delta \log T_e$ is .047 for T Tau, .068 for RW Aur. Figs. 3 and 4 show the emission tracks in the $\log L/L_o$, $\log T_e$ and UBV diagrams after the removal of emission lines.

The most recent spectral type assigned to both program stars is G5Ve (Joy (1960)) but estimates have ranged from G2 to G8. Spectral classification is extremely difficult in this class of variables for two reasons:

1) The absorption lines are obscured by numerous emission lines showing complicated structure.

2) The absorption lines are wide and diffuse.

The wide band photometry included in this work shows $0.50 < B-V < 0.60$ for RW Aur, $1.00 < B-V < 1.17$ for T Tau. These correspond, respectively, to the spectral type ranges F7 - G0 and K3 - K5.

Space reddening affects the B-V continuum color but not the color determined from absorption spectra. This affords an approximate means of determining the space reddening in the vicinity of these stars. Adopting the B-V color corresponding to spectral type G5V one finds $E_{B-V} = 0.46$ for T Tau. The space reddening is essentially zero in the vicinity of RW Aur. There is good agreement with previous work on this problem. RW Aur has no surrounding obscuring nebula as do most other T Tauri stars. Space reddening in its vicinity has long been suspected of being small. Previous estimates of $E_{B-V} = 0.30$ have been given by Herbig (1962) for the Taurus dark cloud. A "continuum classification type" can be obtained by comparing the wavelength distribution of the continuum of the T Tauri star with that of a Code standard, provided the space reddening correction is applied. The continuum spectral type for T Tau redetermined after correction for space reddening
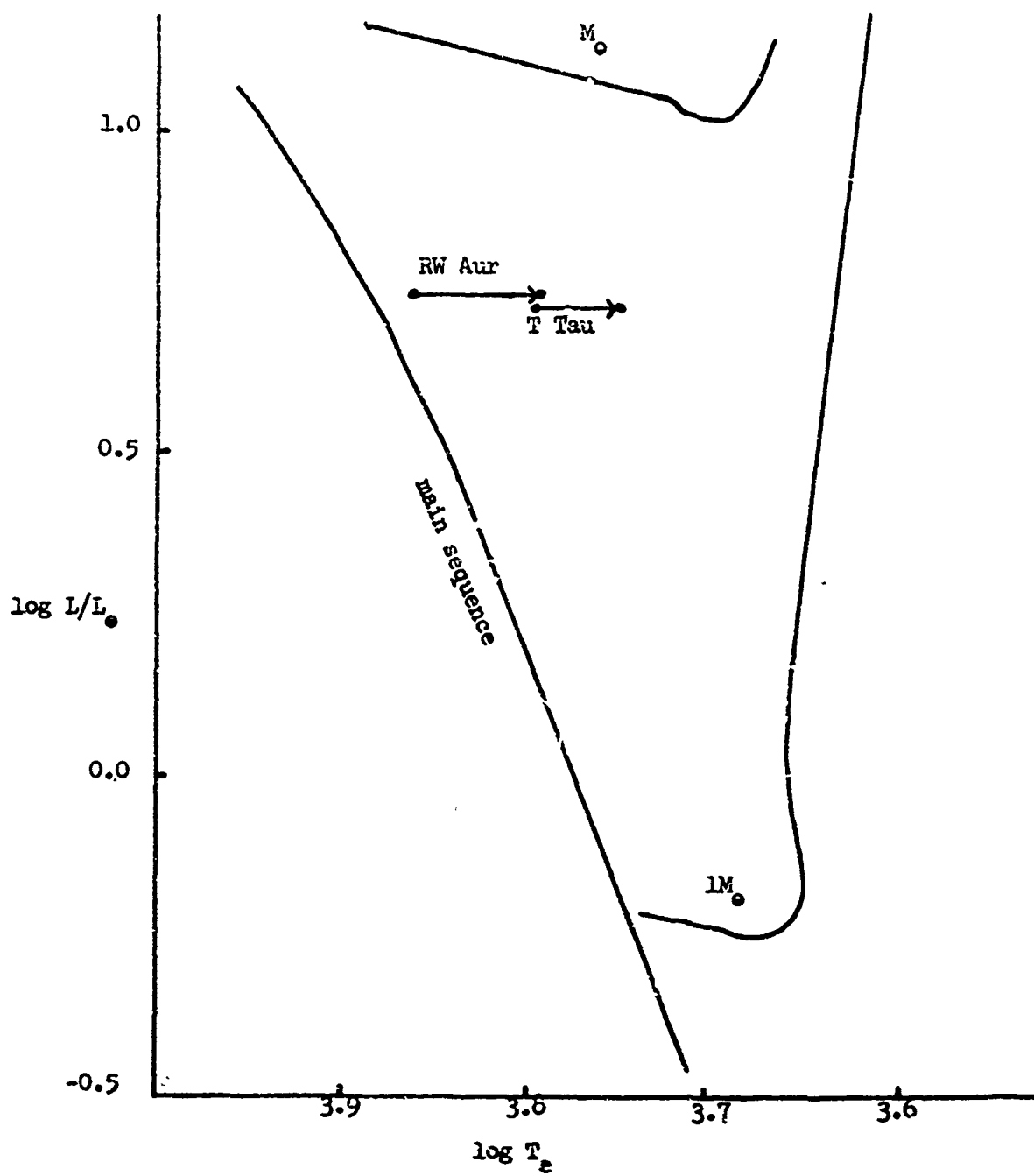
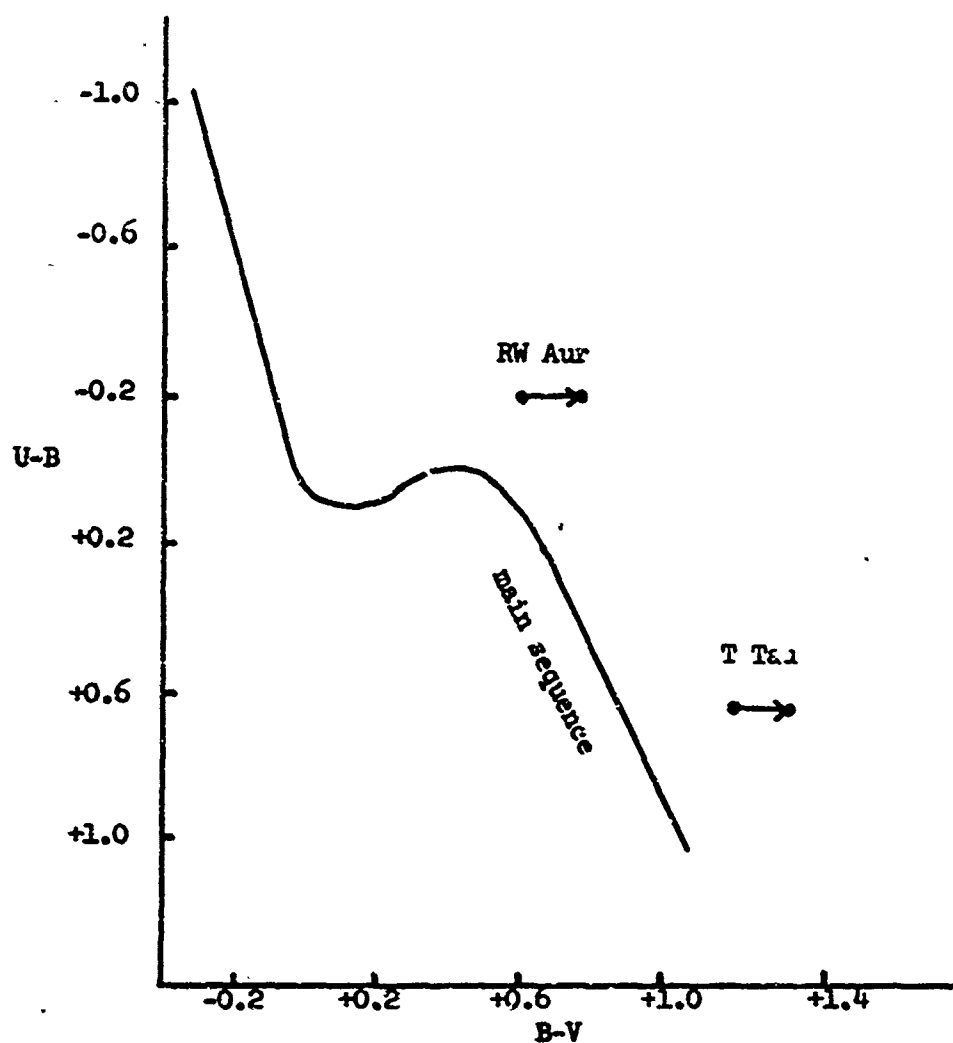Fig. 3. Shift of Position in Log $L/L_\odot$, Tog T_e Diagram After Correction for Emission.

Fig. 4. Shift of Position in the U-B, B-V
Diagram After Correction for Emission in B-V
Correction for U-B was not possible since the
Spectra were not well exposed below λ 3600A.

falls in the range GO - KO. The effective surface temperatures corresponding to the range of types for each star are:

> 5300 - 7600°K for RW Aur (Spectral class mean at F8)

> 5100 - 6300°K for T Tau. (Spectral class mean at G5)

Due to the detailed reduction procedure employed it is necessary to sacrifice large numbers of information elements for the sake of high accuracy. Smak (1964) in attempting to evaluate T Tauri line emission, made use of a filter which is transparent to a region containing relatively few emission lines $(4300 < \lambda < 5100\text{Å})$. He is able to set up a relatively free color base, β- V (the β filter consists of 2mm.EG12 ÷ 2mm. GG3 ÷ 1mm. Corning 3387). Smak's photometric method is extremely useful for compiling vast amounts of data. The low dispersion Steward spectrograms, however, reveal that more than twenty strong emission features exist in the region of β filter transparency. Substitution of the filter for the wide band B filter solves only part of the problem. For Steward Observatory Plate No. 28 of RW Aur, the ratio of emission line to continuum flux in the B passband is 26%. The same ratio in the β passband is 21%. Indeed no filter exists which is completely blind to line emission in these stars. A glance at any of Joy's early spectrograms or Fig. 1 of this paper confirms the statement.

Smak's method of correcting for the emission lines is only partly effective but it might be used as a means of deciding quite rapidly which T Tauri star colors are appreciably altered by the presence of emission lines in their spectra.

References

Code, A.D. 1960, Stellar Atmospheres, ed. G.P. Kuiper and B.M. Middlehurst (Chicago: Univ. of Chicago Press), p. 50.

Herbig, G.H. 1962, Adv. Astron. Astrophys., 1, ed. Z. Kopal, (New York: Academic Press), p. 1.

Joy, A.H. 1945, Ap.J. 102, 168.

_____ 1949, Ap.J. 110, 424.

_____ 1960, Stellar Atmospheres, ed. G.P. Kuiper and B.M. Middlehurst (Chicago: Univ. of Chicago Press), p. 653.

Smak, J. 1964, Ap.J. 139, 1095.

Varsavsky, C. 1960, Ap.J. 130, 354.